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THEORY
OF METALS

Dynamic Model of Spatial Scaling of the Initial Excited State upon Reconstructive Martensitic Transformations

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Abstract—In the dynamic theory of martensitic transformations, the possibility of rapid spatial scaling of the excited state, accompanied by an increase in the transverse size of the region of the initial excited state, was postulated. In this work, it is shown that this postulate corresponds to the process of propagation of a cylindrical wave, which makes it possible to translate information on the type of threshold strain from the nanoscale to the micron level. This model allows one to give a qualitative description of not only the completely twinned midrib of lenticular crystals, but also the partially twinned zone framing the midrib. Another fundamental conclusion is made about the martensitic transformation of austenite nanograins as a whole during the propagation of a cylindrical wave.

Keywords: martensitic transformations, dynamic theory, initial excited state, dislocation nucleation centers, cylindrical wave, transformation of nanograins

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INTRODUCTION

Martensitic transformation (MT) in iron alloys [1] proceeds with pronounced features of a first-order phase transition and refers, as a rule, to the reconstructive variant [2], in which the symmetries of the initial and final phases are not subordinated. The growth rate of the crystals exceeds the velocity of longitudinal elastic waves, which unambiguously indicates the existence and decisive role of a control wave process (CWP) ensuring the cooperative character of the transformation. The start of crystal growth at a temperature M_s (during cooling) is associated with the appearance of an initial excited (vibrational) state (IES) in the elastic field of dislocation nucleation centers (DNCs). Moreover, the CWP inherits information about the deformation field in the IES region and transfers a threshold strain violating the stability of austenite. The process occurs with a significant deviation from the temperature T_0 of the equilibrium of the initial (austenite, γ) and final (martensite, α) phases. These statements reflect the fundamentals of the dynamic theory of MT [3–8], which makes it possible to trace the fundamental relationship between the features of the electronic structure of the γ-phase, elastic fields of DNCs on the one hand and the observed macroscopic morphological features of martensite (metallurgical “visiting card” of MT) on the other.

Particularly striking features are demonstrated by alloys of the invar series (e.g., Fe–(30–32)Ni), in which the magnetic ordering temperature T_c is close to M_s. Such alloys exhibit high spontaneous magnetostriction, leading to an increase in the specific volume δ_s, which compensates the decrease in volume upon cooling. In addition, the high level of magnetic susceptibility in the region of the paraprocess makes it possible to use a strong magnetic field as an effective tool for studying the features of MT [9–12]. These alloys are also characterized by relatively low temperatures M_s. Let us clarify that the temperature M_s depends on the grain size D (see, e.g., [5–7, 13–15]), and there is a critical value of D_c at which $M_s(D_c)$ = 0 K. Therefore, for each alloy, there is a temperature $M_s(\infty) \equiv M_{s\infty}$, which depends on its chemical composition. For invar alloys, not only the temperatures $M_s(D)$, but also $M_{s\infty}$ are below 0°C. Since the value of D_c for Fe–(30–32)Ni alloys is on the order of 1 μm, sufficiently accurate measurements of $M_{s\infty}$ are possible even at grain sizes D ~ 100 μm. However, it should be noted that the addition of carbon rapidly decreases $M_{s\infty}$ and simultaneously increases D_c. For example, $M_{s\infty}$ ≈ 230 K and D_c ≈ 1 μm for the Fe–31Ni alloy, while $M_{s\infty}$ ≈ 165 K and D_c ≈ 10 μm for the Fe–31Ni–0.28C alloy [5, 13]. Therefore, for a relatively accurate measurement of $M_{s\infty}$, a grain size (free from dislocations) of ~1 mm is required.

One of the important results of the dynamic theory of MT is the derivation of an analytical formula for the critical grain size $D_c\left(\Gamma'_e\right)$ of austenite. It is essential that a strong magnetic field under conditions of a positive magnetostrictive change in volume reduces the value of D_c to $D_{cH} < D_c$ and simultaneously increases $M_{s\infty}$ to $M_{s\infty H} > M_{s\infty}$. In particular, according to [5], in the case of a field strength $H = 36$ MA/m for the Fe–31Ni–0.28C alloy, the values $D_{cH} \approx 1.6$ μm and $M_{s\infty H} \approx 245$ K can be expected. Thus, to interpret the results of the action of strong magnetic field, adequate to physical reality, it is necessary to take into account its effect on the change in D_c and $M_{s\infty}$.

Experiments [16], which showed the possibility of cooling austenite without MT and with the subsequent start of MT after heating, demonstrate the absence of a temperature of absolute loss of austenite stability. This fact raises the question of the values of the energy and deformation thresholds separating the phases at the temperature M_s.

Recall that, in the dynamic theory, significant supercooling below the phase equilibrium point T_0 is associated precisely with the need to overcome the interphase barrier, due to the release, during the occurrence of an IES, of energy sufficient for such overcoming, i.e., realization of over-barrier movement in the wave mode. In the general case, the CWP transfers a threshold tensor strain $\hat{\varepsilon}$. In a simplified description, a scalar order parameter in the form of the relative volume change δ can be used. However, this parameter plays an important role, since it is δ that determines the change in the chemical potential of electrons, leading to a change in the contribution of the band energy of itinerant electrons, which is a significant factor in the energy balance. For relatively small threshold strains (δ_{th}),

$$\delta = \delta_{th} \approx \mathrm{Sp}\hat{\varepsilon}, \tag{1}$$

where the symbol Sp denotes the sum of the diagonal components of the strain tensor.

Experiments shows that, in a fairly wide range of H (at least up to 40 MA/m), one can approximately use a linear relationship:

$$\delta_H \approx \lambda_H H, \tag{2}$$

where δ_H is the contribution to δ due to the magnetostriction of the paraprocess. The proportionality coefficient λ_H decreases with increasing distance from the magnetic ordering temperature, but its maximum values are sufficient to satisfy the condition $\delta_H \geq 10^{-3}$ in a strong magnetic field. Within a model with a scalar order parameter [3, 17], the interfacial deformation threshold at a temperature M_s is estimated by $\delta_{th} \approx 5 \times 10^{-4}$. Therefore, it is clear that the contribution of δ_H can have a significant effect at the stage of the onset of an IES in the elastic field of DNCs. It is of interest to refine both the value of δ_{th} and the excess of the threshold strain at the stage of rapid growth of the martensite crystal from independent experimental data.

The aim of this work is to assess the possibility of increasing the transverse size of the IES region at given levels of threshold strain δ_{th} and maximum volumetric strain δ_0 during the IES formation.

1. RATIO OF SPATIAL SCALES AT THE ONSET OF AN EXCITED INITIAL STATE

Despite the fact that the issue of the ratio of spatial scales has been discussed many times (see, e.g., [4, 5, 18]), for the convenience of the readers we will briefly outline and, more importantly, generalize it.

The formation of a CWP is a consequence of an initial "burst": an IES which generates pairs of superimposed (due to diffraction divergence [8]) wave beams. The directions of the wave vectors of the beams $\mathbf{k}_{\ell 1}$ and $\mathbf{k}_{\ell 2}$ are close to the orientations of the eigenvectors ξ_1 and ξ_2 of the strain tensor of the elastic field of the DNCs, corresponding to the principal values of tension, ε_1, and compression, ε_2 (the strain ε_3 along the third vector, ξ_3, is zero or small compared to $|\varepsilon_{1,2}|$). The configuration of the IES region is close to the shape of a rectangular parallelepiped elongated along the ξ_3 axis, spanned on the vectors ξ_i.

In this case, we have the following characteristic ratio of spatial scales:

$$L/d_m \sim 10^2, \tag{3}$$

where d_m is the transverse size of the IES region and L is the size of the dislocations-free grain volume (for a single dislocation in the grain, L coincides with the grain size D). Ratio (3) is the result of two relationships. First, $d_m \sim 0.1r$, where r is the distance from the IES region to the rectilinear segment of the dislocation line. This condition provides an approximate uniformity of the elastic field of the DNC in the IES region. Second, $r \sim 0.1L$, which ensures the dominance of the elastic field of a single DNC.

The subscript m in the notation d_m reflects the choice by the system of the largest transverse size of the IES region that is still compatible with the threshold strain conditions of metastable stable austenite. This requirement ensures the maximum volume-to-surface ratio for the IES localization region and, therefore, contributes to the maximum release of energy in the supercooled system, providing the maximum relaxation rate. It should be noted that, with increasing distance from the temperature T_0, δ_{th} decreases and the difference between the specific free energies of the phases increases. The elastic field of the

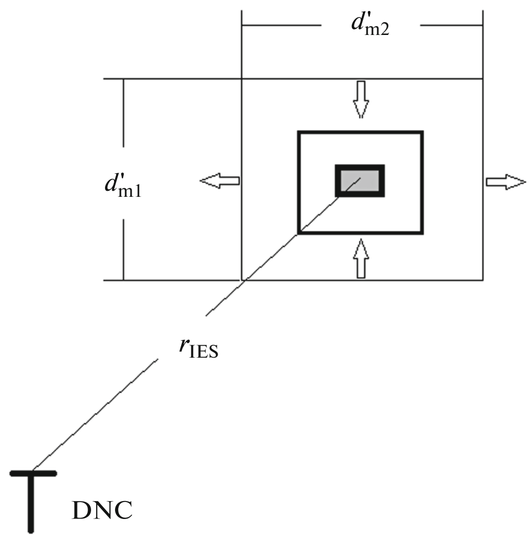

Fig. 1. Diagram showing the dependence of the cross section of the IES region on the ratio between δ_0 and δ_{th}: the gray smallest rectangle corresponds to the case $\delta_0 \approx \delta_{th}$, the other two variants are $\delta_0 > \delta_{th}$. The directions of the arrows reflect the difference in the signs of strains in the orthogonal directions.

rectilinear segment of the line of an individual DNC at a distance r from the segment leads to a strain

$$\varepsilon \sim 0.1a/r, \tag{4}$$

where a is the lattice parameter. Note that, in the dynamic theory of MT, the habits of the {3 10 15} crystals observed in the 30N31 alloy are unambiguously put into correspondence with 30-degree mixed dislocations as DNCs. Calculation of the elastic field of such DNCs shows that the maximum δ corresponds to $\approx 0.05\ a/r$. Consequently, for a known δ_{th}, the IES localization region and the value of d_m can be specified by the values

$$r_{IES} \approx 0.05a/\delta_{th},\ d_m \approx 0.1r_{IES}. \tag{5}$$

If the maximum strain δ_0 in the vibrational mode (due to the energy released in the IES volume) slightly exceeds δ_{th} (that is, $\delta_0 \geq \delta_{th}$), then wave beams with wavelengths $\lambda_{1,2} \sim 2(d_m)_{1,2}$ form a prototype of a martensite crystal, specifying the orientation of its habit. The transverse sizes $d_{1,2}$ determine the crystal thickness:

$$d = \sqrt{d_1^2 + d_2^2} \approx d_m\sqrt{2}. \tag{6}$$

Moreover, in the harmonic description of waves, $d_{1,2} < \lambda_{1,2}/2$. The largest size (length) of the growing crystal is achieved in a direction collinear to the vector sum of the wave velocities and is limited by the scattering of waves by obstacles such as grain boundaries or previously formed martensite crystals. The width of the crystal is determined by the size of the IES region in the ξ_3 direction and is limited by a size of the order of $\Lambda/2$, where Λ is the length of the rectilinear segment of the dislocation loop, which plays the role of a DNC.

However, with significant supercooling with respect to T_0, the release of energy in the volume of the IES region can lead to the inequality $\delta_0 \gg \delta_{th}$. Then, instead of exciting pairs of wave beams generating a CWP (or along with such beams), the IES region can increase the transverse sizes up to $(d'_m)_{1,2}$ during the propagation of a cylindrical wave (CW), as is schematically shown in Fig. 1.

Note that the phases of vibrations in the vertical and horizontal directions are opposite and, as a result, the strains in these directions, have different signs. As noted in [5], by virtue of the law of conservation of energy, an expanding CW excited at time t_0 with an initial wavefront curvature radius $\rho(t_0) \equiv \rho_0$ and an oscillation amplitude $u_0 = u(t_0)$ at time $t > t_0$ is characterized by $\rho(t)$ and $u(t)$ under the condition

$$u_0^2\rho_0 = u^2\rho. \tag{7}$$

It is clear that the maximum strain on the wave axis is given by the ratio of the amplitude to the radius. Therefore, from (7), we obtain a strain ratio

$$\varepsilon_0/\varepsilon = \delta_0/\delta_{th} = (\rho/\rho_0)^{3/2} = (d'_m/d_m)^{3/2}. \tag{8}$$

Then, e.g., at a strain $\delta_0 = 10\delta_{th}$, from (8) and (5), it follows that, at constant r_{IES}, the size d'_m will exceed d_m by a factor of $(10)^{2/3} \approx 4.64$. Thus, for $\delta_0 \gg \delta_{th}$, ratio (3) is transformed to

$$L/d'_m \sim 10^2/(\delta_0/\delta_{th})^{2/3}. \tag{9}$$

Obviously, under condition (9), the wavelengths of the excited wave beams and the thickness d of the martensite crystal will increase by a factor of $(\delta_0/\delta_{th})^{2/3}$. Recall that the concept of the rapid formation of an IES region with a transverse size $2\rho \sim d$ was introduced in [19], where an IES is termed macronucleus (in [3], this term is also present as a tribute to the previous terminology).

In the case of spontaneous (during cooling) fcc—bcc rearrangement due to the Bain distortion (see, e.g., [1]), $\delta_B = 0.024$ can be taken as a typical change in the specific volume. Then, the maximum threshold strain is given by the value of $\delta_B/2$ and this value can naturally be attributed to the temperature T_0. To reflect the temperature dependence of the threshold strain $\delta_{th}(T)$ at $T_0 \geq T \geq M_s$, we use the simplest approximation

$$\delta_{th}(T) = \delta_{th}(M_s) + [(\delta_B/2) - \delta_{th}(M_s)](T - M_s)/(T_0 - M_s). \tag{10}$$

It is obvious from (10) that $\delta_{th}(T) \to \delta_B/2$ as $T \to T_0$ and $\delta_{th}(T) \to \delta_{th}(M_s)$ as $T \to M_s$. Note that, due to the release of energy in the bulk of the IES region, the temperature increases and, according to (10), $\delta_{th}(T) > \delta_{th}(M_s) \equiv \delta_{th}$. Along with the strain δ_{th}, necessary for the onset of the IES and the onset of the CWP, an important role is played by δ_0: the maximum strain in the vibrational mode in the bulk of the IES region. The level δ_0 specifies the initial intensity of the cylindrical expansion wave and, under the condition

$$\delta > \delta_{th}(T) \tag{11}$$

one may expect for δ_0 the values

$$\delta_0 \geq \delta_B/2 = 1.2 \times 10^{-2}. \tag{12}$$

2. ANALYSIS OF DATA ON THE INCREASE IN CRYSTAL THICKNESS IN A STRONG MAGNETIC FIELD

Figure 2 presents the experimental data of [9, 20].

It can be seen from Fig. 2 that, with a linear dependence $d(H)$, the slope ratio is

$$\begin{aligned} \Delta d/\Delta H &\approx (3/28) \times 10^{-6}\ \mathrm{m^2/MA} \\ &\approx 1.07 \times 10^{-7}\ \mathrm{m^2/MA}. \end{aligned} \tag{13}$$

In addition, at $H = 4$ MA/m, the thickness is $d \approx 0.5$ μm; therefore, using (13), at $H = 0$, we obtain $d_0 \approx 0.072$ μm. Then, $d_m \approx d_0/\sqrt{2} \approx 0.05$ μm and, according to (5), $r_{IES} \approx 0.5$ μm. This means that, for $a \approx 3.6 \times 10^{-10}$ m, we obtain $\delta_{th} \approx 0.05a/r_{IES} \approx 3.6 \times 10^{-5}$.

This estimate is an order of magnitude lower than the aforementioned purely qualitative estimate $\delta_{th} \approx 5 \times 10^{-4}$ in [3, 17]. It is clear that the introduced value of δ_{th} is dictated by the requirement for the onset of IES1 in the elastic field of an individual dislocation, corresponding to the spontaneous formation of a thin-lamellar crystal (at $H = 0$). Thus, henceforward, as a reference point, we assume that the value of δ_{th} is close to the minimum threshold strain for martensite cooling in the 30N31 alloy.

According to [9], the real thicknesses of thin-lamellar crystals of cooling martensite are 0.2–0.3 μm; i.e., are 3–4 times larger than the value obtained by the linear extrapolation to the zero field of the dependence $d(H)$. This provides evidence in favor of the mechanism of $d_m \rightarrow d'_m$ transformation of the IES due to the propagation of CWs, in accordance with (8) and (9).

In addition, the experimental data [9, 20] indicate a linear dependence of the critical magnetic field on the displacement (ΔM_s) of the temperature M_s, so that

$$\Delta H/\Delta M_s \approx 1.25\ \mathrm{MA/mK}. \tag{14}$$

We assume that the shift $\Delta M_s > 0$ is determined by the dominance of the positive contribution of the volume magnetostriction of the paraprocess, δ_H, over the negative contribution from the decrease in the spontaneous magnetization. Then, the use of the technique described in [15] makes it possible to determine the value of the resulting constant $\lambda_H \approx 1.1 \times 10^{-5}$ (MA/m)$^{-1}$, corresponding to (14). Note that, with this λ_H (MA/m)$^{-1}$, the value of $\delta_H = \lambda_H H$ at $H = 4$ MA/m exceeds the found threshold value δ_{th}. Therefore, during a strong field pulse, for $\tau \sim (10^{-4}–10^{-3})$ s, the rapidly (in a time of the order of 10^{-7} s) formed crystal of thin-lamellar martensite has the possibility of lateral growth stimulated by the magnetic field. This variant of growth is associated with the propagation of a trigger-type wave [3, 17, 21], which, in the absence of a CWP, has a velocity v_{tr} much lower than the speed of sound. As applied to our case, it is obvious that, for a time $\tau = 10^{-3}$ s, one-sided lateral growth by $\Delta d = 1$ μm is associated with the value $v_{tr} \approx \Delta d/\tau = 1$ mm/s. The choice of the value $\Delta d = 1$ μm for estimating v_{tr} is consistent with the experimental data (see Fig. 2). A more detailed consideration of the lateral growth mechanism associated with the modification of the trigger wave under the action of a strong magnetic field is beyond the scope of this article. We only note that the lateral growth of thin-lamellar crystals (preserving the lamellar shape) in tensile stress fields was observed in [22].

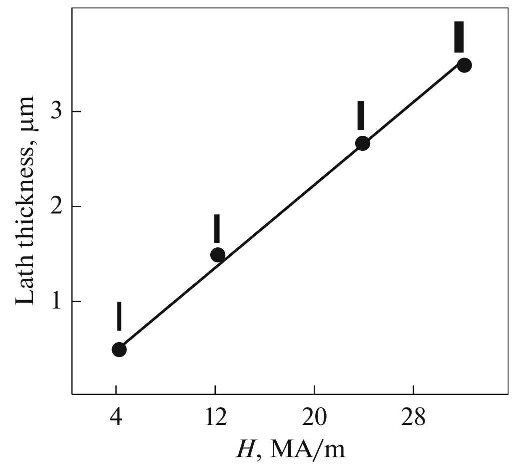

Fig. 2. The thickness of martensite crystals of the 30N31 alloy vs. the magnetic field strength (the thickness of the martensite crystals is schematically shown above the curve).

Note, as an alternative to the lateral growth mechanism, that an increase in the crystal thickness can also be associated with an expanding CW and the formation of an IES2 region with a transverse size $d'_m > d_m$.

Relationships (5) and (8) imply a relationship between δ_{th}, d'_m, a, and δ_0:

$$\delta_0 = (\delta_{th})^{5/2}[d'_m/(5 \times 10^{-3} a)]^{3/2}. \tag{15}$$

For example, let us consider the case of $H = 32$ MA/m and $d = 3.5$ μm. Assuming $d'_m \approx d/\sqrt{2} \approx 2.5$ μm, for the already used values of a and δ_{th}, from (15), we find $\delta_0 \approx 1.27 \times 10^{-2}$, which corresponds to the expected values $\delta_0 \geq \delta_B/2$. This result indicates the consistency of the parameter values and, at least, correct orders of magnitude. Using at $\delta_0 \approx 1.27 \times 10^{-2}$ and $\delta_{th} \approx 3.6 \times 10^{-5}$ the ratio $\delta_0/\delta_{th} \approx 352.8$, from (8), for $d'_m \approx 2.5$ μm, we obtain $d_m \approx 0.05$ μm; i.e., the CW is triggered from the IES1 localization region, which is located at a distance $r_{IES1} \approx 0.5$ μm from the dislocation line. Recall that the IES1 state has already been discussed by us in connection with the initiation of the growth of a thin-lamellar crystal. Obviously, due to the CW excitation, there is a genetic linkage between the IES1 and IES2.

It is clear that we can introduce IES0, assuming that the CW comes from a localization region with a transverse size d_{m0}, located at a distance r_{IES0} from the dislocation line. Using the same ratio $\delta_0/\delta_{th} \approx 352.8$ from (8) with the substitutions $d'_m \to d_m$ and $d_m \to d_{m0}$, we find $d_{m0} \approx 1$ nm and $r_{IES0} \approx 10$ nm. Thus, theoretically, a two-stage transfer of information about the elastic field of a defect can occur due to CWs from compact nanoscale regions.

At a fixed ratio δ_0/δ_{th}, thicknesses $d < 3.5$ μm correspond to smaller values of H, d'_m, d_m, and r_{IES}, or, with fixed r_{IES}, the values of δ_0 decrease: for example, $d = 0.5$ μm at $H = 4$ MA/m corresponds to $\delta_{01} \approx 6.77 \times 10^{-4}$ and a ratio $\delta_{01}/\delta_{th} \approx 18.8$.

3. DISCUSSION OF THE RESULTS

The change in the transverse size of the IES region due to the propagation of a CW essentially clarifies the statement that was previously used as a postulate [3, 18].

In the geometric limit, when the Bain cell is deformed and an IES region with the smallest possible size $d_m = a$ appears, due to the cylindrical expansion of the IES, the transformation of most of the nanograins as a whole is possible (at $\delta_{th} \approx 3.6 \times 10^{-5}$, the diameter of the grain undergoing MT is $D \approx d'_m \approx 60.5a \approx 22$ nm).

From (8), it is clear that limiting the value of δ_0 by $\sim\delta_B/2$ would allow, as a result of one cylindrical expansion, to go from $d_m = a$ to transverse sizes $d'_m = 1$ μm, sufficient to describe crystals of micron thickness, only if the value of δ_{th} is reduced to 10^{-7}. This value of δ_{th} seems to be underestimated. At the same time, the two-stage variant of cylindrical expansion from $d_m = a$ to $d'_m = 1$ μm with preserving $\delta_{th} \approx 3.6 \times 10^{-5}$ looks quite realistic.

Scenarios of the appearance of IES regions with two transverse scales seem promising when interpreting the formation of a partially twinned zone adjacent to the midrib, which is characteristic of lenticular crystals (the periphery of such crystals has a complex dislocation structure). Indeed, assume that the IES1 region with a size $d_m \sim 0.1$ μm simultaneously starts the formation of a midrib and the excitation of an expanding CW, which leads to the appearance of an IES2 region with a size $d'_m \sim 1$ μm. The midrib growth proceeds at a supersonic speed with a coordinated action in the CWP1 relative to the long-wave pair of waves (ℓ1-wave), which are responsible for the formation of the midrib boundary (crystal habit), and relatively short s-waves, which are responsible for the formation of the main component of the twin structure (TS1) of the midrib. Since the formation of IES2 is delayed in relation to IES1, the excited pair of ℓ2 waves in the CWP2 favors the transformation in the lamellar region, the central part of which is the midrib. Recall [23] that, upon the formation of a regular TS, active s-cells appear in the center of the lamellar region, which is already occupied by the midrib. This means that, in the area surrounding the midrib, the formation of a relatively regular TS is unlikely. As a result, in the regions adjacent to the midrib, a partially twinned structure arises, associated with the spontaneous activation of s-cells near the midrib, where the contribution to the threshold strain from the ℓ2 waves is greater.

Note that, when the CW starts from the IES0, i.e., from a nanoscale region, the conclusions of the dynamic theory, based on the calculations of the elastic fields of the DNC within the continuum theory of elasticity, remain valid, since the distance from the dislocation segment is still an order of magnitude larger than the size of the dislocation nucleus. The start of a CWP from IES0 and the supersonic growth of martensite crystals on s-waves seems to be difficult because of the high decay rate of the s-waves [24]. However, the expansion of the CW can cause the emergence of IES1 and IES2, giving rise to stable CWPs.

The use of the term "lath" in relation to a martensite crystal in [9] indicates the relative proximity of the thickness d and width b of the crystal (it is assumed that $b > d$). As noted above, the width of the crystal is determined by the size of the IES region in the ξ_3-direction and is limited by a size of $\approx\Lambda/2$. This limitation is associated with the requirement of approximate uniformity of the elastic field in the IES region, which is violated when approaching the curved sections of the dislocation line. Taking $d = 3.5$ μm and $b \sim (1.5–2)d$, it can be assumed that the length of the rectilinear segment is $\Lambda \approx 10–14$ μm. Obviously, the requirement of uniformity of the elastic field will be fulfilled only at small (compared to Λ) values of $r_{IES} \leq 0.1\ \Lambda$. Thus, even a separate DNC dictates the ratio of the spatial scales, which are essential at the onset of an IES. It should be noted that the variant of IES1 discussed above satisfies these relations.

The estimates made above do not take into account the dissipation processes, as well as the possible amplification during the propagation of the CWs in an active medium. In particular, this may refer to the mutual compensation of such processes.

CONCLUSIONS

Estimating calculations have shown that the description of thin lamellar crystals with a thickness of ~0.1 μm is consistent with the concept of the onset of an IES in the elastic field of a single DNC, if the threshold strain at a temperature M_s is $\delta_{th} \approx 3.6 \times 10^{-5}$.

It has been shown that, in a strong pulsed magnetic field, a possibility of a lateral growth of a thin lamellar crystal at a rate of ~1 mm/s arises, which is six to seven orders of magnitude lower than the formation rate of the initial crystal due to the action of a CWP.

Based on the analysis performed, it is easy to understand that the scaling of the IES region associated with the propagation of a CW makes it possible to provide conditions for the onset of the growth of a martensite crystal in the field of an individual DNC even at relatively high dislocation densities (up to $\approx 10^{10}$ cm^{-2}).

Explicit consideration of the processes of spatial scaling of the IES region extends the abilities of the dynamic theory of MT both in describing the transformation of nanocrystals and in interpreting the formation of lenticular crystals.

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